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A WEDGE TEST FOR QUANTIFYING FULLY PLASTIC FRACTURE

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microscopic examination of the fracture surfaces indicated that the wedges suppress blunting, the presence of non-zero initiation displacements suggests that a fracture process zone of finite thickness must be established before crack growth. During growth, a specimen with rolling direction normal to the crack plane had a crack growth ductility (minimum displacement per unit ligament reduction) of 0.006-0.009, compared to ductilities of 0.016-0.027 for specimens with rolling direction parallel to the crack front or parallel to the growth direction. The lower ductility with the crack normal to the rolling direction appears to be due to a smoother fracture surface without zigzagging between inclusion stringers.

A WEDGE TEST FOR QUANTIFYING FULLY PLASTIC FRACTURE

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Abstract

A test using two wedges splitting a small, doubly grooved specimen
allows measurement of stable, fully plastic crack initiation and growth
under variable amounts of triaxiality. In wedge tests, 25mm cubes of 1018
hot rolled steel in three different orientations exceeded the limit load
predicted by plastic slip-line fields. The tests gave crack tip
initiation displacements of 0.7-0.8mm, regardless of orientation. Since
microscopic examination of the fracture surfaces indicated that the wedges
suppress blunting, the presence of non-zero initiation displacements
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established before crack growth. During growth, a specimen with rolling
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to the crack front or parallel to the growth direction. The lower
ductility with the crack normal to the rolling direction appears to be due
to a smoother fracture surface without zigzagging between inclusion
stringers.

Introduction and Proposed Test

If cracking occurs in a structure. it is desirable that the remaining
ligament be fully plastic during fracture, to provide stability by load-
sharing with other parts of the structure, and to provide large
deflections that increase the chance of detecting impending ailure.

Drawbacks of existing plastic fracture tests. a) They tend to be
unstable (e.g. Clausing 1970). b) They tend to require specimens several
centimeters long. c) They involve appreciable crack-tip blunting.

d) There is no simple way to vary triaxiality while keeping approximately the same test configuration.

(A short rod fracture test developed by Barker (1977,9) is suitable for small specimens, but only if they are predominantly elastic, with K_{Ic} of interest.)

Features of the wedge splitting test. Consisting of two knife-like wedges splitting a doubly grooved cubic specimen (Fig. 1a), the wedge test has the following features that overcome some of the above drawbacks.

1) Stability. Low specimen and apparatus compliances make stable crack initiation and growth possible.

2) Small specimen size. The size is limited only by homogeneity of the material and the amount of displacement required for crack initiation.

3) Blunting suppression. During initiation, the wedges suppress blunting (and therefore help to provide crack-tip triaxiality), as shown by the experiments and the following slip-line argument. According to the fully plastic displacement fields that occur at various stages, and are discussed below, until crack initiation the ligament contracts by no more than the groove half-opening. The wedge advance is the groove half-opening divided by the tangent of the wedge half-angle. Thus for half-angles less than 45°, the wedge continually advances into the material in the remaining ligament, suppressing blunting.

4) Variable triaxiality and strain distribution. Triaxiality can be varied from test to test by varying the wedge angle. For especially low triaxiality, the test allows splitting two singly grooved specimens that have been placed back to back (Fig. 1b; for analysis, see Hill 1953). As we shall see below, a complication does arise from the increasing triaxiality with incresing length of wedge-specimen contact.

The strain distributions around the crack tip can be varied by using unequal or tilted wedge angles (Figs. 1c,d). Tilted wedge angles could be used to model a cutting-off operation.

These features suggest that the wedge splitting test can give further insight into fully plastic fracture, especially for small specimens cut from welds, anisotropic plate, or irradiated material.

Difficulties associated with small size. Analyzing the test is made

more difficult by small size. Recall that physically, ductile fracture
from a pre-existing crack involves first blunting of the crack tip, until
the combination of strain and stress extends over a large enough region to
nucleate holes and to grow them enough to coalesce into a macrocrack. The
crack tip profile then sharpens abruptly as the crack begins to grow.
That is, the relative displacement across the net section per unit crack
growth is small compared to unity. At the same time, the regions of
highest strain lie above and below the plane of the crack. This promotes
roughening of the crack surfaces because parts of the crack momentarily
run up or down. The advance of the crack is irregular by a corresponding
amount. (In general, there is little evidence that holes nucleate more
than one hole spacing ahead of the main crack.) The extent of this
lateral roughening and irregular front constitutes a fracture process zone
which is not treated by ordinary continuum mechanics, and which is
relatively pronounced in small specimens.

The strain for hole growth depends exponentially on the triaxiality
(McClintock, 1968). High triaxiality occurs: a) if the plastic zone is
contained within an elastic zone, b) if there is sufficient strain
hardening for a Hutchinson (1968) and Rice and Rosengren (1968) (HRR)
singularity, or c) if a fully plastic specimen is subject to bending or
to tension across symmetrical edge grooves. In a region of the order of
the hole spacing, the resulting high triaxiality limits the strain to
fracture to a few percent. Averaged over the fracture process zone, the
strain is even less. It is reduced still more when localization of flow
occurs before the holes would join under homogeneous plasticity. Thus a
specimen may hardly reach full plasticity unless it is very small, in
which case there may not be room for the HRR singularity to develop
between the boundaries of the part and the fracture process zone, which
requires strains of only a few percent.

A further complication in small specimens is that during initiation
and early crack growth, the combination of strain and triaxiality in the
remaining ligament may initiate fracture there. If so, the concept of
growth of the crack from the original tip no longer applies.

Characterizing fracture. In large enough specimens, fracture can be

characterized by the strength $k_I = k_{Ic}$ of the linear elastic stress
singularity that dominates in a region large compared to the fracture
process zone and small compared to the crack length or distance to the
next nearest boundary. The crack is almost immediately unstable. In
smaller specimens, there may be a similar region dominated by the
nonlinear elastic HRR singularity. Initiation can then be defined in
terms of a critical value of J. As noted above, this dominance is
unlikely for the small strains required to initiate fracture by hole
growth under high triaxiality, and the relatively flat initial stress-
strain curve (see, for example, Shih 1985, McMeeking and Parks 1979, Shih
and German 1981). For crack growth, the singularity should be one of the
new ones developed for bi-linear, flow theory, elastic-plastic material
(Slepyan 1973,4, Ponte-Castañeda 1985). Here again the question arises as
to whether the singularity dominates in a region at least somewhat larger
than the fracture process zone. Finally, there may be so little strain
gradient across the remaining ligament that the plastic flow might be
described by non-hardening solutions (such as those reviewed by
McClintock 1971). While non-hardening solutions may give good
approximations to the stress field, and tolerable approximations to the
displacements, they often indicate discontinuities in displacement
increments, and hence in strain rates, that would be diffused by even an
infinitesimal amount of strain hardening.

In conclusion, there is no precise way of characterizing the stress
and strain fields for fracture in wedge tests. Here, as a reasonable
compromise, we describe the results in terms of solutions for non-
hardening plasticity .

Specimens and Apparatus

Figure 2 shows the test specimen and wedge splitting apparatus.
Cubic specimens of 1018 hot-rolled steel (equivalent Brinell hardness 108
kg/mm^2 HB) were proportioned using upper-bound limit analysis to avoid
shearing off the specimen shoulders. The 22.2mm cubes had 45^0 grooves
machined in two opposing faces, leaving a 2.5mm ligament.

Three specimen orientations were tested. The ASTM designates orientations by a pair of the three directions in the rolled stock: the longitudinal L , the long transverse T , and the short tranverse S (ASTM E399, 1985). Growing tensile cracks are denoted by a pair of directions, the first direction being the normal to the crack plane and the second the direction of crack propagation. Orientations for cracks in square bars are denoted as follows.

1) Rolling direction normal to the crack plane, L-T.

2) Rolling direction parallel to the crack growth direction, T-L.

3) Rolling direction parallel to the crack front, T-S.

The apparatus is described from the specimen outward. Strips of 0.09mm thick Teflon $\circledR$ tape minimized friction between the specimen and wedges. During the tests, the Teflon $\circledR$ remained continuous but thinned to 0.03mm.

The wedges were of 6.4mm thick tool steel (614 kg/mm^2 HB equivalent), 14mm from tip to base. Since preliminary tests with wedges of 45° included angle were unstable during half of the load drop, 43° wedges were used in the tests discussed below.

Short, square, steel bases supported the wedges. Safety shoulders on the bases were to contain the sample if there should be a dynamic fracture. Adjustable stops mounted between the bases prevented the wedges from damaging each other.

Deformation was imposed by a 50 metric ton MTS hydraulic testing machine, with a measured machine compliance of 1.7×10^{-6} mm/N. The specimen compliance, measured with a 23mm gauge length between points on the wedges, was found on unloading to be 2.0×10^{-6} mm/N. The splitting jig compliance, found by subtraction of machine and specimen compliances from the overall compliance found from the MTS stroke control, was 6.6×10^{-6} mm/N. This system gave stable tests for the 43° wedges.

Analysis of Wedge Test Slip-Line Fields

The plastic slip-line displacement fields of Fig. 3 give stress distributions and limit loads at several points during the loading history. Their triaxiality (say $\sigma_{max}/\bar{\sigma}$) is nearly that of the elastic or

HRR singularities.

For a reference field, consider the slip-line displacement field derived by Neimark (1968) for a doubly grooved bar in tension. This configuration is approximated in the wedge test when the wedge angle is slightly greater than the groove angle, so that contact occurs at the specimen shoulders (Fig. 3a). The maximum principal stress σ_{1N}, across the ligament OT, is given in terms of the yield strength in shear k and the included wedge angle ω, by

$$\sigma_{1N} = k(2 + \pi - \omega) \quad . \tag{1}$$

If the wedge angle is less than the specimen groove angle, initial contact is made at the tip and spreads backward along the flank, according to a modification of the wedge indentation solution by Hill, Lee, and Tupper (1947; see also Hill, 1985, pp. 215-221). When the region of contact has spread to Point A' (Fig. 3b), plastic flow occurs all across the ligament according to the flow field of Hill (Hill 1985, pp. 245-252). The maximum principal stress, σ_{1H}, across the ligament is affected by the pressure on the flank. The effect can be found using the Hencky equations of equilibrium along α and β slip lines (Hill 1985 p. 135). The mean normal stress σ changes with the counterclockwise rotation $d\phi$ of an α line from the x axis (see Fig. 3a):

$$d\sigma = 2 k d\phi \quad \text{along an } \alpha \text{ line },$$
$$d\sigma = -2 k d\phi \quad \text{along a } \beta \text{ line } . \tag{2}$$

In terms of the wedge-specimen contact pressure p_w, and with no friction, the mean normal stress at A' is $\sigma_{A'} = -p_w + k$. In terms of σ_{1H}, the mean normal stress at O is $\sigma_O = \sigma_{1H} - k$. The change in mean normal stress from A' to O is found by applying the second Hencky equation, along a β line, through an angular change $\Delta\phi = -(\pi/2 - \omega/2)$:

$$(\sigma_{1H} - k) = (-p_w + k) + 2k[\pi/2 - \omega/2] \quad . \tag{3}$$

From a balance of x-forces on the right half of the specimen, $p_w \cos \omega/2 =$

σ_{1H} . Solving for σ_{1H} gives the form

$$\sigma_{1H} = k \ (2 + \pi - \omega) \ \frac{\cos \omega/2}{(1 + \cos \omega/2)} \ . \tag{4}$$

For displacements, even infinitesimal strain hardening diffuses any discontinuities, but the general character of the displacement fields remains. Therefore, the non-hardening fields should provide insight for fracture in the wedge test. The displacements u and v along α , β lines, respectively, must satisfy the Geiringer equations of incompressibility (Hill 1985 p. 136):

$$du = v \ d\phi \quad \text{along} \quad \text{an } \alpha \text{ line } ,$$
$$dv = -u \ d\phi \quad \text{along} \quad \text{a } \beta \text{ line } . \tag{5}$$

The strain is given in terms of radii of curvature R , S of the α , β slip lines. In terms of distances s along the slip lines (Hill 1985 p. 138).

$$1/R = \partial\phi/\partial s_\alpha \quad ,$$
$$1/S = -\partial\phi/\partial s_\beta \quad . \tag{6}$$

Relative to slip lines, the deformation is pure shear strain obtained from the Green equation (1953, see also McClintock 1971 p. 130):

$$\gamma_{\alpha\beta} = \frac{\partial v}{\partial s_\alpha} + \frac{u}{R} + \frac{\partial u}{\partial s_\beta} + \frac{v}{S} \ . \tag{7}$$

For a splitting displacement U across the specimen, the Hill flow field has a constant displacement relative to the right-hand side of $v = -U/\sqrt{2}$, giving rigid-body displacements in Regions TA'B' and TC'D. Eq. 7 gives a strain singularity at the tip of the fan B'TC', where the radius $S = -r$ goes to zero:

$$\gamma_{\alpha\beta} = v/S = U/\sqrt{2}r \ . \tag{8}$$

There is also a displacement discontinuity [v] = U/√2 along A'B'C'D. As

the wedges penetrate, the material flows down and to the right through OC', acquiring a shear strain of 2.

The crack tip opening displacement (CTOD) for the Hill field is twice the splitting displacement, as shown in Fig. 3b.

The next known flow field, as the wedge penetrates, corresponds to the Prandtl solution (Prandtl 1920, see also Hill 1985 pp. 254-255). It occurs when there is contact from T to A' (Fig. 3c). The maximum principal stress in the ligament for the Prandtl field, σ_{1P}, is found from an analysis similar to that for the Hill field:

$$\sigma_{1P} = k \ (2 + \pi - \omega) \ \frac{2 \cos \omega/2}{(1 + 2 \cos \omega/2)} \ . \tag{9}$$

The displacement field for wedge contact along TA consists of a constant displacement $v = -U/(2\sqrt{2})$ in the rigid regions TAB and OTC. The shear strain at the tip in the fan BTC is correspondingly reduced by a factor of 2 from that of Eq. 8 for the Hill field. There is in addition the displacement discontinuity $[v] = U/(2\sqrt{2})$ along TC.

Again, the Prandtl field holds only for a moment, here when contact extends from T to A. At some later time the material will draw away from the wedge except at the very tip, and the Neimark field will be approximated. The Neimark field consists of displacements along BT that increase linearly from 0 to $U/\sqrt{2}$. Within the central constant-state region bordering OT, the strain is uniform at U/ℓ , where ℓ is the current ligament. From Fig. 3a, the CTOD for the Neimark field is twice the splitting displacement, as it was for the Hill field.

Choosing a 45° total wedge angle would promote loading away from the root of the groove and tend to give the Neimark slip-line field immediately. In the experiments, a total wedge angle of 43°, less than the 45° groove angle of the specimen, was required for stability. It promoted loading near the root of the groove, giving first the Hill, then the Prandtl, and finally the Neimark slip-line fields as the contact moved outward.

Interpretation of Data

For comparison with tensile data, the reported loads are the
splitting loads, (normal to the ligament), found under the assumption of
negligible friction by dividing the measured wedge loads by the tangent of
the wedge half-angle. Similarly, the splitting displacements are the
relative wedge displacements times the tangent of the wedge half-angle.

Figure 4 shows a typical loading curve for the T-S orientation
(rolling direction parallel to the crack front). The loads are normalized
with respect to the original Neimark limit load F_{N0}, based on the
specimen breadth b, the original ligament ℓ_0, and the yield strength
$\sqrt{3}\ k = HB/3$ (in consistent units). The splitting displacements are
normalized with respect to the original ligament ℓ_0.

Choice of a measure of initiation displacement U_1, comparable to
the crack tip opening displacement, is rather arbitrary. Initially in the
loading curve of Fig. 4, the displacement is due to compression of the
Teflon® tape. Elastic-plastic and flank deformation displacements occur
until the Hill field is reached at 0.43 of the Neimark limit load. The
subsequent slope of the loading curve is still much less than the elastic
one, apparently due to the changing flow fields. As a compromise, take
the point of zero plastic displacement to be that found by extrapolating
the maximum slope of the loading curve backward from the point of
inflection to zero load.

The point of crack initiation is that at which a crack begins to run
ahead of the wedges. In a fully plastic, non-hardening material this
would be indicated by a drop in stress based on the drop in splitting load
P, the current wedge tip separation $\ell_0 - U/\tan(\omega/2)$, and the specimen
breadth b:

$$\sigma = \frac{P}{b[\ell_0 - U/\tan(\omega/2)]} \,. \tag{10}$$

Such true stresses are indicated by the sloping lines in Fig. 4,
where they have been normalized with respect to σ_{N0}, the maximum
principal stress of the Neimark field based on the original ligament. In

a strain hardening material, the true stresses would be rising. Crack initiation would at first only slow down that rise, and the point of maximum stress would be after crack initiation. Nonetheless, for definiteness and consistency with the use of non-hardening stress fields, take crack initiation to occur at the point where the stress σ of Eq. 10, shown in normalized form by the sloping lines of Fig. 4, is a maximum.

The crack growth ductility D_g can be defined as the minimum splitting displacement dU (normal to the crack plane) per unit ligament reduction $d\ell$ (Kardomateas 1985). The splitting displacement dU arises from the applied displacement dU_{app} due to the advancing wedges and the elastic unloading displacement dU_{unl} .

$$dU = dU_{app} + dU_{unl} \quad . \tag{11}$$

Assuming no strain hardening gives the load drop dP per unit ligament reduction in terms of the Neimark limit load based on the original ligament:

$$dP/d\ell = P_{NO}/\ell_O \quad . \tag{12}$$

The crack growth ductility is now found from measurable quantities by introducing Eqs. 11 and 12:

$$D_g = \frac{dU}{d\ell} = \frac{dU_{app} + dU_{unl}}{\ell_O \ dP/P_{NO}} \quad . \tag{13}$$

Results and Discussion

Table 1 lists the results in terms of the net section stresses and splitting displacements at initiation, according to the above criteria, and also the crack growth ductility.

Crack initiation. As shown by Fig. 4, the load at first rose rather rapidly in the plastic range, as the 43° wedges made contact farther out along the flank. The initiation stresses of Table 1 are above unity,

suggesting that the full triaxiality of a doubly grooved tensile bar had been reached, even allowing for some strain hardening and frictional effects.

The initiation displacements were $U_i = 0.35-0.42$mm , corresponding to CTOD $\approx 0.7-0.8$mm . These initiation displacements are comparable to the 0.88mm crack tip displacements at initiation for single edge-notched (low triaxiality) tensile specimens found by Kardomateas (1985) for 1018 normalized steel.

Microscopic examination of the fracture surfaces showed smearing of the first portion of the surfaces, occurring over the first 50-60% of the half-ligament. This initial smearing suggests that the wedge tips indented the root of the groove before initiation, suppressing blunting, as expected from the displacement fields.

Since initiation displacements are still present in the wedge tests, there seems to be a need for establishing a fracture process zone of finite thickness or roughness before crack growth, regardless of triaxiality. We are indebted to Prof. D.M. Parks for pointing out that a similar phenomenon occurs in splitting wood: even a sharp axe must be driven a finite distance into wood before a crack spreads ahead of it.

Crack growth. The T-S and T-L orientations (rolling directions parallel to crack front and parallel to growth direction, respectively) gave growth ductilities of $D_g = 0.016-0.027$. The ductility of the single L-T specimen (rolling direction normal to crack plane) was only 0.006-0.009, however. This low growth ductility is at first surprising, because this orientation has the highest initiation ductility in an unnotched specimen.

For the notched specimens, these differences in crack growth ductility can be explained by considering the fracture surfaces. Microscopic examination showed that the T-L and T-S specimens (Fig. 5a) had comparably rough, jagged fracture surfaces zigzagging along and across inclusion stringers, perhaps due to multiple initiation sites and directions along the wedge tips. The average surfaces seemed to be convex, corresponding to accelerating crack growth from the wedge tips. The L-T specimen (Fig 5b) had a much smoother surface, with holes

perpendicular to the fracture plane. The average fracture surface was S-shaped (see also Hancock and Cowling 1980). It is possible that the absence of inclusions in the crack plane allowed the crack to follow a path governed by the stress and strain fields, independent of the location of individual inclusions. The matching fracture surfaces of the L-T specimen also suggest that strain and high triaxial stress in the ligament may have initiated a single fracture in the center of the ligament, which then propagated outward toward the wedges. Sectioning specimens at various stages of fracture should be done to resolve this question. The higher ductilities associated with the T-S and T-L orientations were probably caused by rougher crack surfaces associated with zigzagging. Such roughness would be absent in homogeneous materials with low inclusion density, or with long inclusions normal to the ligament.

Even the largest of these growth ductilities is only one-tenth of the value of 0.258 found by Kardomateas (1985) in symmetric notched tensile specimens of 1018 normalized steel. These smaller ductilities for the wedge test are probably due to the higher triaxiality.

Microscopic inspection of the wedges showed 0.10-0.15mm tip deformation, even after tests on the relatively soft 1018 steel. Thus wedge deformation may be significant when testing hard materials. In such cases it may be possible to decrease wedge tip deformation by using wedges made of tungsten carbide or cubic boron nitride.

Conclusions

1. The wedge splitting test allows stable, fully plastic crack initiation and growth in small specimens. Triaxiality varies with the wedge angle and the length of wedge-specimen contact.

2. Even with blunting suppressed, the crack tip initiation displacements of 0.7-0.8mm suggest that a process zone of finite thickness or roughness is necessary before crack growth. This displacement corresponds to a splitting displacement of half as much, and is comparable to that observed in SEN specimens of 1018 normalized steel.

3. The one specimen of orientation with a rolling direction normal

to the crack plane (L-T) had a crack growth ductility of 0.006-0.009,
compared with ductilities of 0.016-0.027 for orientations with rolling
direction parallel to crack growth (T-L) or parallel to the crack front
(T-S). The low growth ductility for the L-T orientation is associated
with a smooth fracture surface and is attributed to lack of zigzagging
between inclusion stringers. The difference between these ductilities and
that of 0.258 for symmetric notched tensile specimens of 1018 normalized
steel is attributed to the higher triaxiality in the wedge test.

4. The specimen size can be decreased only to the point where the
inhomogeneous effects of hole nucleation and growth become important. At
that point, the above ductility parameters become statistical and size-
dependent.

5. Increasing strain in the ligament, as the crack progresses, leads
to an accumulation of damage that would give at best a quasi-steady crack
growth.

Acknowledgments

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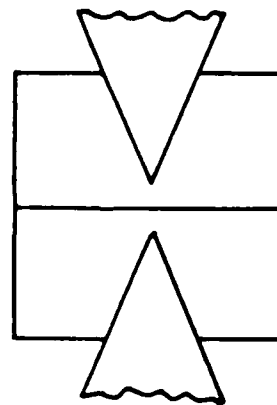 668, J.D. Landes, J.H. Begley, and G.A. Clarke, eds., Am. Soc.

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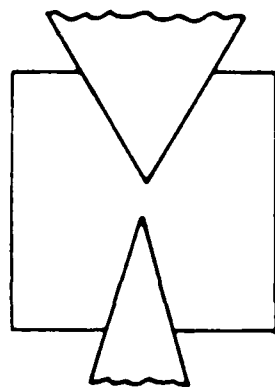Table 1.   Wedge Splitting Test Data. 1018 Hot Rolled Steel

Specimen orientation (crack normal)-(growth dir)	Normalized stress at initiation σ/σ_N (current ligament)	Splitting displacement at initiation $U_1 \approx CTOD/2$ mm	Crack growth ductility D_q
T-S	1.23	0.40	0.022
T-S	1.16	0.36	0.016
T-S	1.33	0.36	0.021
T-L	1.09	0.35	0.025
T-L	1.27	0.36	0.027
L-T	1.29	0.42	0.006-0.009
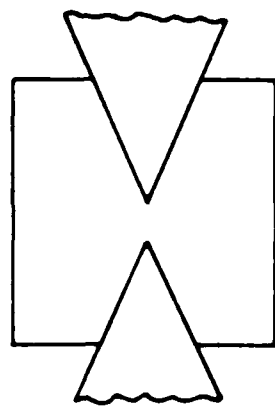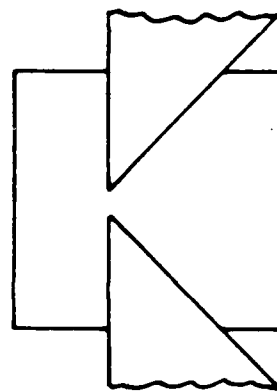
Figure 1. (a) Wedge configuration tested. (b) Low
triaxiality configuration. (c) Unequal wedge angles.
(d) Tilted wedge angles.
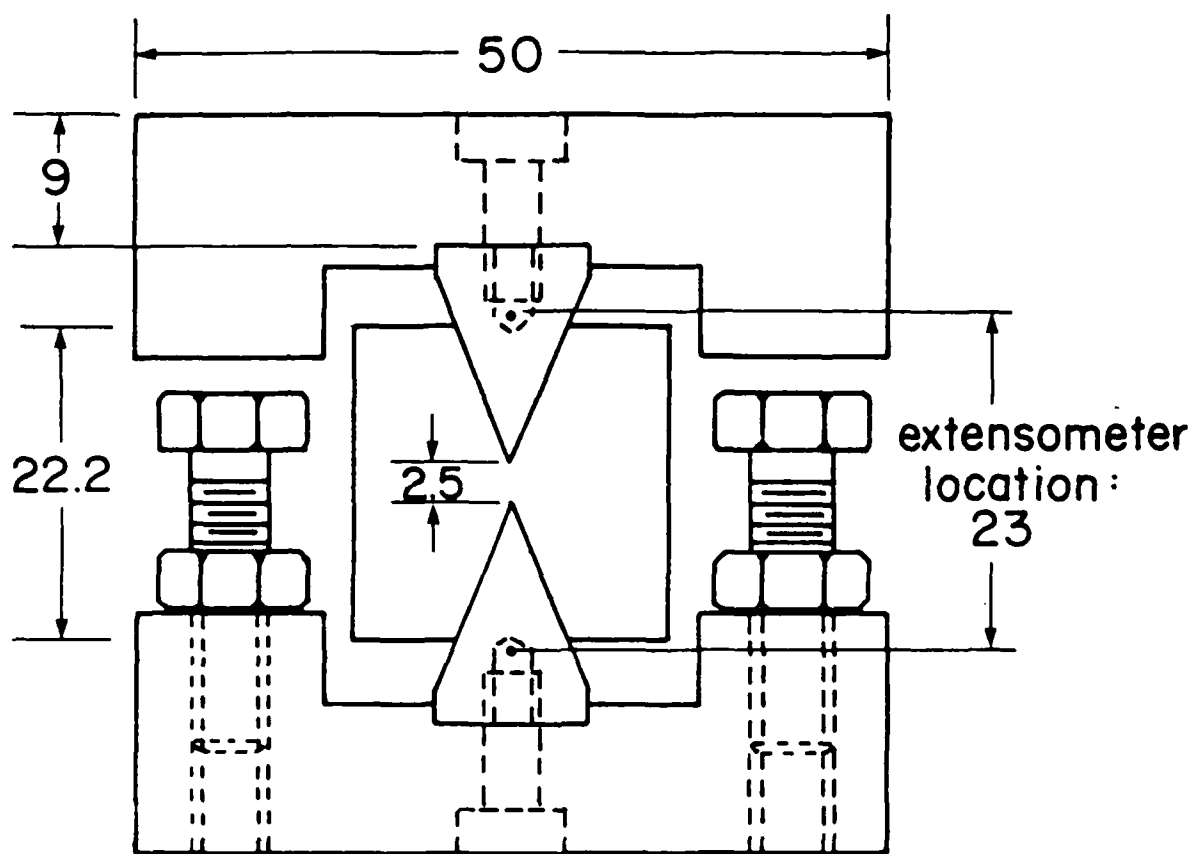
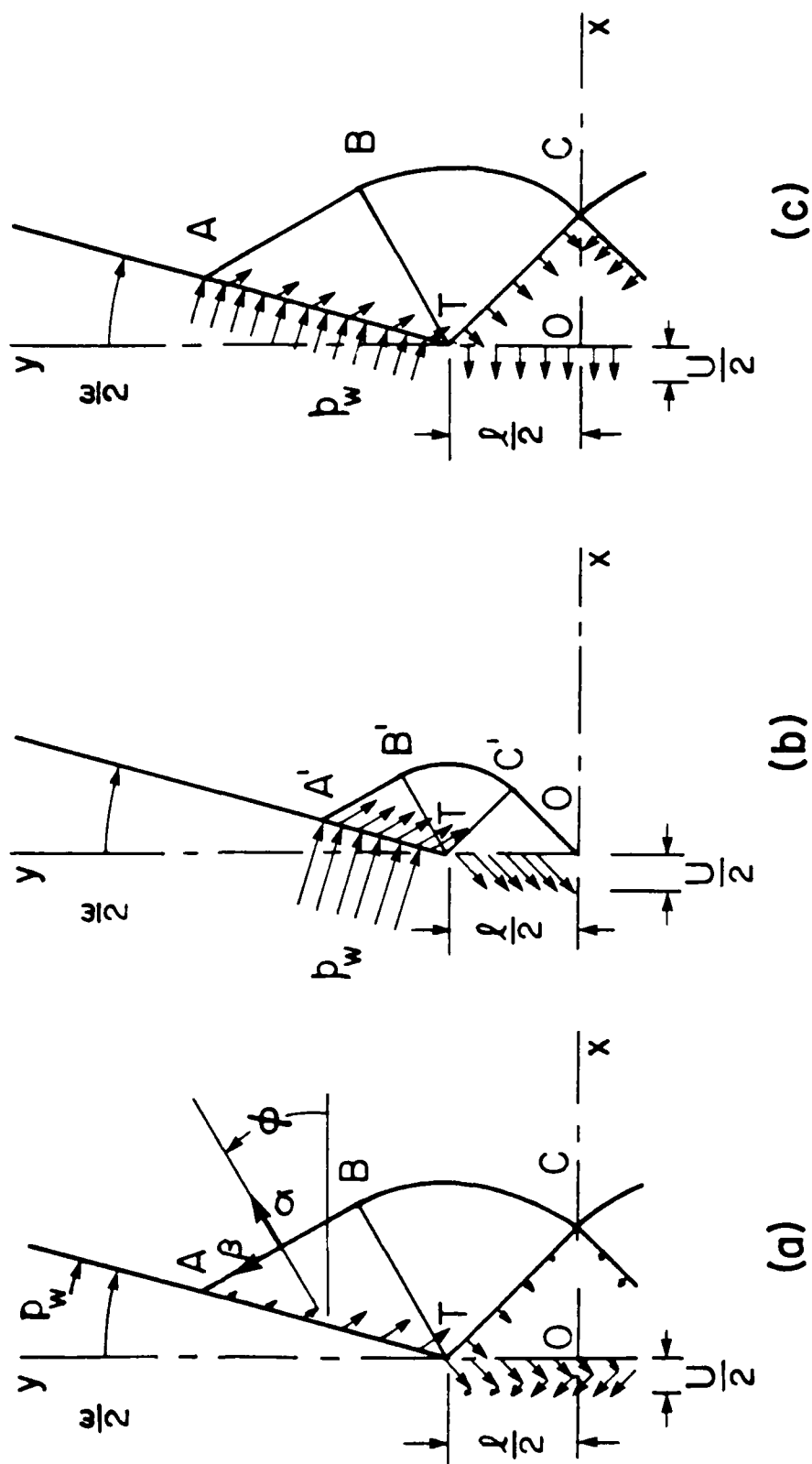Figure 2. Specimen and apparatus. Dimensions in mm.

Figure 3. Displacement fields for the wedge test, relative to the right-hand side of the specimen. (a) Nelmark field; shoulder contact. (b) Hill field; contact out to half the ligament length. (c) Prandtl field; contact out to the ligament length.
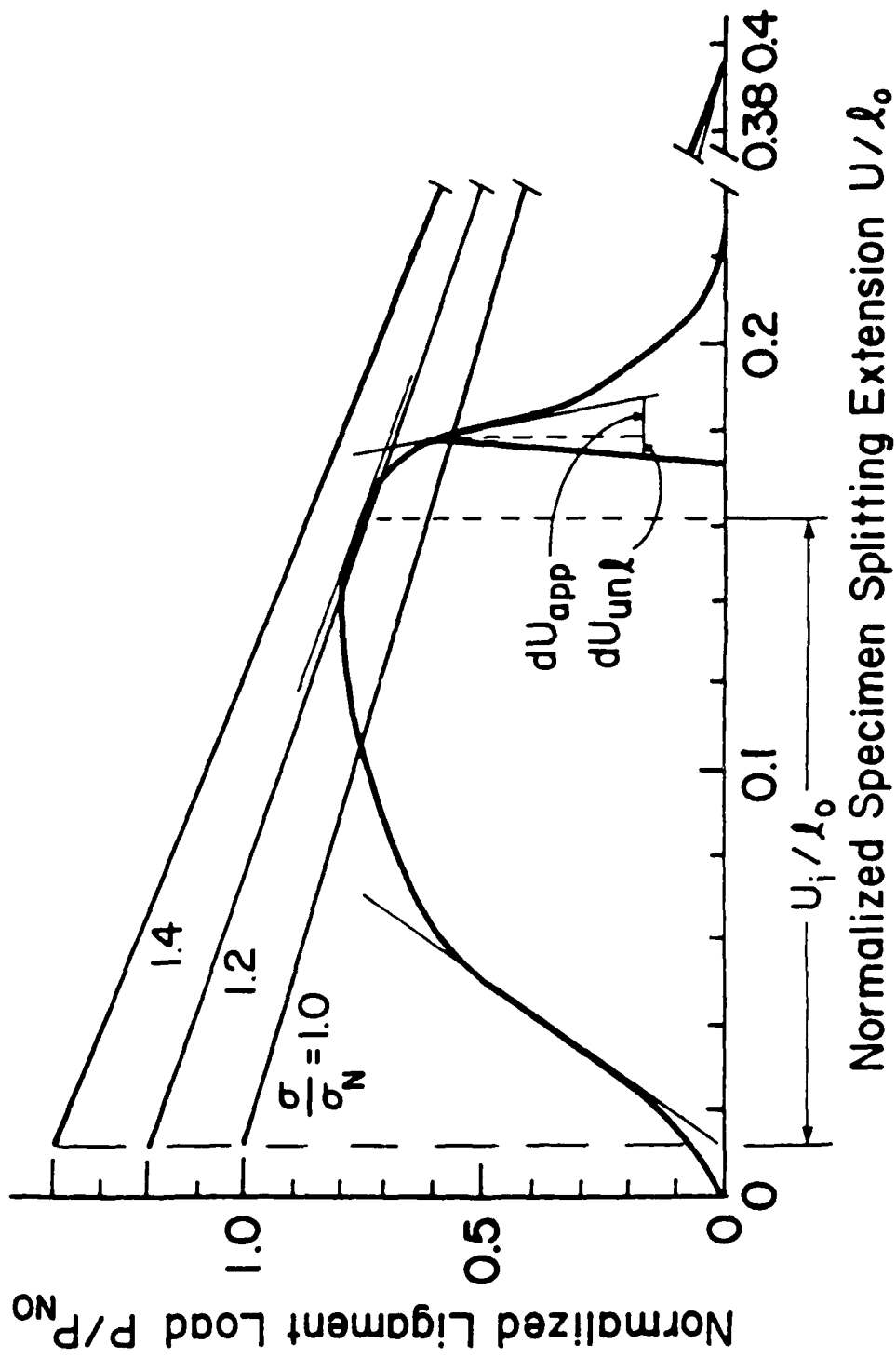
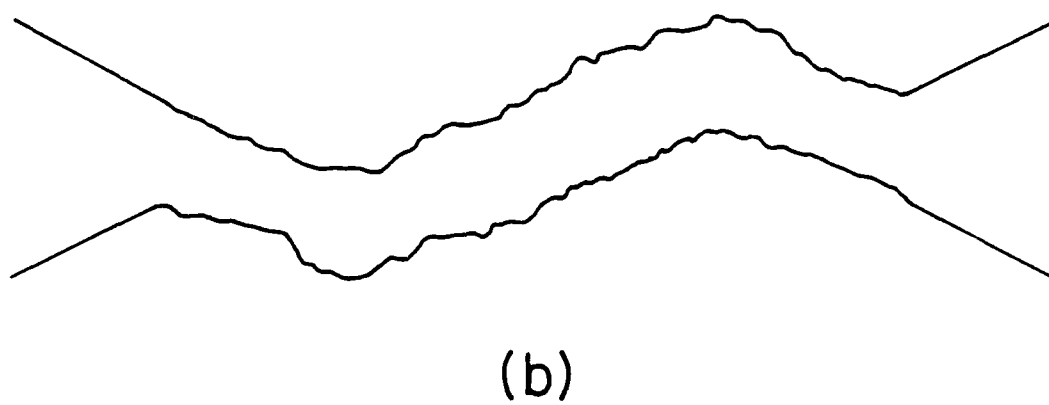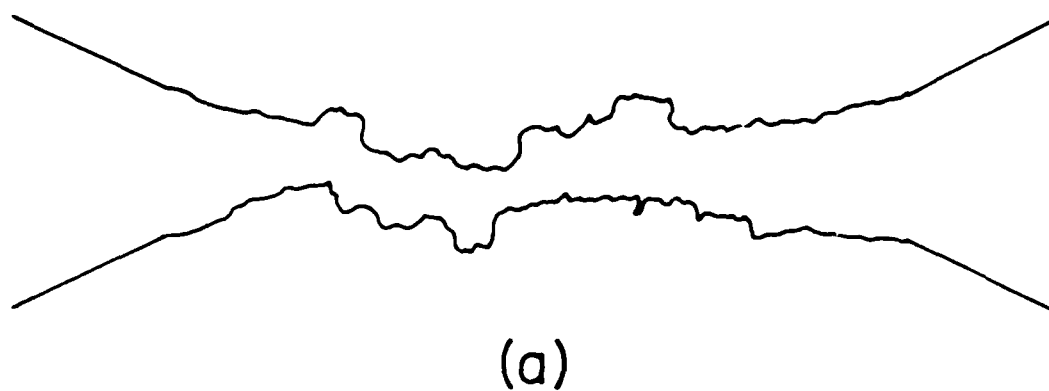Figure 4. Typical loading curve for T-S orientation.

Figure 5. Schematic of the fracture surface profiles.
(a) T-S and T-L orientations. (b) L-T orientation.

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